

Description

[METHOD FOR DETERMINING PROPERTIES OF FORMATION FLUIDS]

BACKGROUND OF INVENTION

[0001] FIELD OF THE INVENTION

[0002] This invention relates to techniques for determining properties of formations surrounding an earth borehole and, more particularly, to a technique for downhole determination of the resistivity of fluids extracted from earth formations.

[0003] BACKGROUND OF THE INVENTION

[0004] The resistivity of fluids in earth formations is known to be a very important indicator of the nature of the formations. The well logging art contains numerous approaches to indirect and direct determination of formation fluid resistivity. [In the present application, any references to determination or use of resistivity are intended to generically mean conductivity as well, and vice versa. These quanti-

ties are reciprocals, and mention of one or the other herein is for convenience of description, and not intended in a limiting sense]. Several techniques are commonly used to measure the resistivity of the formations (the fluid and the matrix containing the fluid) using measurements from a logging device in the borehole, which, for example, can employ electrodes to perform so-called "normal" or "lateral" resistivity logging, or coils to perform induction logging. Electrodes can also be used for spontaneous potential ("SP") logging to determine formation water resistivity. It has also been proposed that formation resistivity can be determined by measuring the impedance looking into an antenna coil in a borehole, the antenna also serving a source of RF energy for a companion NMR technique (see U.S. Patent 5,831,433).

[0005] The resistivity of formation fluid samples drawn from the formations by a logging device, such as a so-called formation testing tool, can be measured directly downhole, and this is typically performed using electrodes spaced apart in the fluid. However, a problem with contact measurements of fluid resistivities is that the electrodes can be wetted by one of the fluids. This may bias the measurements. Another problem is that when measurements

are made in vertical or highly deviated wells, the effects of gravity segregation of the fluids typically results in measurement errors unless the fluids are flowing.

[0006] It is among the objects of the present invention to provide a method for downhole determination of formation fluid resistivity which is efficient to practice and which overcomes shortcomings of prior art approaches.

SUMMARY OF INVENTION

[0007] The present invention is directed to a method for downhole determination of the resistivity of fluids from formations surrounding an earth borehole. An embodiment of the method of the invention includes the following steps: providing a formation testing logging device that includes a coil and a flow line passing axially through the coil; determining a reference quality factor of the coil; positioning the formation testing device in the borehole, and causing formation fluid to flow through the flow line; measuring the quality factor of the coil with formation fluid in the flow line; and determining the resistivity of the formation fluid in the flow line as a function of the measured quality factor and the reference quality factor. The step of measuring the quality factor can be performed as formation fluid flows axially through the coil, or with formation fluid

axially within the coil and non-flowing. An embodiment of the invention further includes providing a Faraday shield between the coil and the flow line, the shield being operative to prevent electrical lines of force associated with distributed capacitance from passing through the formation fluid within the coil during said step of measuring the quality factor of the coil.

[0008] In a further embodiment of the invention, both the dielectric constant and the resistivity of formation fluid in the flow line are determined.

[0009] The invention has advantageous application to so-called formation testing well logging devices that draw fluids from earth formations, but can also be employed in other settings, examples being measurement while drilling or measurement while tripping.

[0010] Further features and advantages of the invention will become more readily apparent from the following detailed description when taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF DRAWINGS

[0011] Figure 1 is a diagram, partially in block form, of a formation testing logging device of a type that can be used in practicing embodiments of the invention.

- [0012] Figure 2 is a diagram of an electrical coil, and an electrically non-conductive flow line passing axially through the coil.
- [0013] Figure 3 is a diagram useful in illustrating calculation of inductive losses in a conductive sample.
- [0014] Figure 4 is a schematic diagram for an equivalent circuit of a tuned circuit with dielectric loss.
- [0015] Figure 5 is a graph of series resistance due to inductive loss as a function of sample conductivity for a solenoid used in an experiment.
- [0016] Figure 6 is a graph of series resistance due to dielectric loss plotted as a function of sample conductivity at various frequencies.
- [0017] Figure 7 shows experimental data of series resistance as a function of conductivity at various frequencies.
- [0018] Figure 8 is a graph showing calculated and experimental series resistance as a function of sample conductivity at 2.37 MHz.
- [0019] Figures 9 and 10 are graphs showing calculated and experimental series resistance as a function of sample conductivity at 9.88 MHz. In Figure 10, lower conductivities are shown in further detail.
- [0020] Figures 11 and 12 are graphs showing calculated and ex-

perimental series resistance as a function of sample conductivity at 19.655 MHz. Figure 12 shows lower conductivities in further detail.

[0021] Figure 13 is a graph showing theoretical and experimental data of quality factor, Q , at 2.37 MHz.

[0022] Figure 14 is a graph showing theoretical and experimental data of quality factor, Q , at 9.8 MHz.

[0023] Figure 15 is a graph showing theoretical and experimental data of quality factor, Q , at 19.655 MHz.

[0024] Figure 16 illustrates an embodiment utilizing a Faraday shield.

[0025] Figure 17 is a flow diagram of the steps of a routine for practicing an embodiment of the invention.

[0026] Figure 18 is a diagram of equipment used in implementing an embodiment of the invention.

[0027] Figure 19 and 20 are flow diagram of routines in accordance with an embodiment of the invention.

[0028] Figure 21 is a graph useful in understanding operation of an embodiment of the invention.

[0029] Figure 22 is a graph showing theoretical and experimental data of series resistance as a function of sample conductivity at 18.225 MHz, with use of a Faraday shield.

DETAILED DESCRIPTION

[0030] Figure 1 shows the borehole 32 that has been drilled, in known manner, with drilling equipment, and using drilling fluid or mud that has resulted in a mudcake represented at 35. A formation tester apparatus or device 100 is shown, and can be used in practicing embodiments of the invention. The apparatus 100 is suspended in the borehole 32 on an armored multiconductor cable 33, the length of which substantially determines the depth of the device 100. Known depth gauge apparatus (not shown) is provided to measure cable displacement over a sheave wheel (not shown) and thus the depth of logging device 100 in the borehole 32. Circuitry 51, shown at the surface although portions thereof may typically be downhole, represents control and communication circuitry for the investigating apparatus. Also shown at the surface are processor 50 and recorder 90.

[0031] The tool 100 has an elongated body 105 which encloses the downhole portion of the apparatus, controls, chambers, measurement means, etc. One or more arms 123 can be mounted on pistons 125 which extend, e.g. under control from the surface, to set the tool. The device includes one or more probe modules, each of which includes a probe assembly 210 which is movable with a

probe actuator (not separately shown) and includes a probe (not separately shown) that is outwardly displaced into contact with the borehole wall, piercing the mudcake and communicating with the formations. The equipment and methods for taking pressure measurements and doing formation fluid sampling are well known in the art, and the logging device 100 is provided with these known capabilities. Reference can be made, for example, to U.S. Patent Nos. 3,934,468 and 4,860,581, which describe early versions of devices of this general type.

[0032] Modern commercially available services utilizing, for example, a modular formation dynamics tester ("MDT" – trademark of Schlumberger), can provide a variety of measurements and samples, as the tool is modularized and can be configured in a number of ways. Examples of some of the modules employed in this type of tool, are as follows: An electric power module is generally provided. It does not have a flowline or hydraulic bus, and will typically be the first (top) module in the string. A hydraulic power module provides hydraulic power to all modules that may require same, and such power can be propagated via a hydraulic bus. Probe modules, which can be single or plural probes, includes pistons for causing en-

gagement of probe(s) for fluid communication with the formations. Sample modules contain sample chambers for collecting samples of formation fluids, and can be directly connected with sampling points or connected via a flow-line. A pumpout module can be used for purging unwanted fluids. An analyzer module uses optical analysis to identify certain characteristics of fluids. A temperature measurement capability is also provided. A packer module includes inflatable packer elements which can seal the borehole circumference over the length of the packer elements. Using the foregoing and other types of modules, the tool can be configured to perform various types of functions. An embodiment of the present invention has application to tool configurations which draw formation fluid into the tool and, typically, although not necessarily, return the fluid into the borehole. As first noted above, the resistivity of the formation fluid in the flow line can be measured using spaced apart electrodes in the fluid. The present invention utilizes a different technique, which overcomes limitations of prior art approaches.

[0033] It is known in the art that formation fluid in the flowline of the formation testing logging tool can be subjected to nuclear magnetic resonance (NMR) measurements by provid-

ing a coil (e.g. coil 210 in Figure 2) through which formation fluid can pass axially in an electrically non-conductive portion of the flowline (e.g. 110 of Figure 2), the coil being used to produce and receive rf energy in the presence of a static magnetic field produced by permanent magnets (not shown). (Reference can be made, for example, to U.S. Patent 6,346,813.) In an embodiment of the present invention, the same coil (210) can be utilized in a technique for downhole determination of formation fluids. It will be understood, however, that, if desired, a different coil on the flowline can be used in this embodiment. Signals under control of the processor(s) are coupled with the coil via leads 192.

[0034] Some of the theory relating to operation of the invention will next be set forth.

[0035] A tuned antenna includes an inductor (L), capacitor (C), and a resistor (R) in series or in parallel combination. The quality factor of the tuned circuit (Q) is given as

[0036] $Q = \text{Energy Stored} / \text{Energy Loss} = \omega L / R, (1)$

[0037] where ω is the operating frequency, L is the inductance of the coil, and R is the series resistance of the circuit.

[0038] In air, the losses in the antenna mainly come from all the components (e.g., inductor, capacitor) in the tuned circuit.

The resistive losses of the antenna in air are determined by parameters such as copper losses, capacitor losses, ferrite losses (if a ferrite is used). The internal loss is denoted as R_{int} and the quality factor of the tuned circuit is

[0039] $Q = \omega L / R_{int} \quad (2)$

[0040] In addition to internal losses, there can also be losses due to the sample under test. The sample losses could be due to inductive and/or dielectric losses (see "The Sensitivity of the Zeugmatographic Experiment Involving Human Samples," DI Hoult, PC Lauterbur, JMR, 34, 425–433, (1979); "Radiofrequency Losses in NMR Experiments on Electrically Conducting Samples," DG Gadian, FNH Robinson, JMR, 34(2) 449–455, (1979); "Noise in MRI," A Macovski, Mag. Reson. Med. 36, 494–497, (1996)).

[0041] Inductive losses are associated with the conductivity of the sample. The radiation of RF EM fields from the coil, induce eddy current in a conducting sample, which dissipate power. The power dissipation can be expressed as an effective resistance R_L in series with the inductor. This loss cannot be avoided, but it can be estimated from the physical dimensions of the coil and the sample.

[0042] The loss caused by the induced voltage is determined by first calculating the average power dissipated from an ap-

plied voltage. The dissipated power is used to calculate the effective series resistance R_L . The calculation of this loss is as follows: The resultant loss caused by the induced voltage is determined by first calculating the power dissipated from an applied voltage and using that power to calculate the effective series resistance R_L . For simplicity, assume a cylindrical solenoidal coil surrounding the fluid sample as shown in Figure 3. The principle of reciprocity is used to calculate the effective series resistance. The coil is excited with unity peak amplitude current ($I_0=1$), $I = I_0 \cos \omega t$. The resultant average power dissipated by the conducting sample is given as

[0043]
$$P_{av} = W = I_0^2 R_L / 2 = R_L / 2, (3)$$

[0044] where, I_0 is the peak sinusoidal current (unity in this case).

[0045] The magnetic field in the solenoid, which is assumed to be uniform, is given by

[0046]
$$B_1 \sim n \mu_0 I / (2 * \sqrt{a^2 + g^2}) (4)$$

[0047] where n is the number of turns, μ_0 is the permeability of vacuum, a is the radius of the coil, and $2g$ is the length of the solenoid.

[0048] The voltage, V_p , induced in the cylindrical shell at a distance r is given by

[0049] $V_p = -d\Phi/dt = -A dB_1/dt = \pi r^2 \omega (n \mu_0 / (2 * \sqrt{a^2 + g^2})) \sin \omega t$ (5)

[0050] where $A = \pi r^2$ is the area subtended by the cylindrical shell. The peak induced voltage, V_p , is used to calculate the average power dissipated in the shell as given by

[0051] $dW = (V_p^2 / 2) dG$ (6)

[0052] where, the differential conductance of the cylindrical shell, dG , is given

[0053] $dG = 2g dr / (2\pi r \rho)$ (7)

[0054] Integrate dW over the entire cylinder to find the total dissipated power

$$W = \int dW = \int_0^{r_0} (\pi r^2 \omega (n \mu_0 / (2 * \sqrt{a^2 + g^2})))^2 (2g dr / 4\pi r \rho) \quad (8)$$

[0055] The effective resistance, R_L , is then given by

[0056] $R_L = 2 W = \pi \omega^2 n^2 \mu_0^2 g r_0^4 / (16 * \rho * (a^2 + g^2))$ (9)

[0057] The series resistance can be calculated at various frequencies (ω) for given solenoid parameters (n , g , and a) as a function of resistivity (ρ).

[0058] As just set forth in (9), the effective resistance of the sample in series with the inductor is given as

[0059] $R_L = 2 W = \pi \omega^2 n^2 \mu_0^2 g r_0^4 / (16 * \rho * (a^2 + g^2))$

[0060] where $\omega (= 2 \pi f)$ is the angular frequency, n is the num-

ber of coil turns, g is half the coil length, r_0 is the radius of the test tube containing the sample (the flow line, in this case), a is the radius of the coil, ρ is the resistivity of the sample, μ_0 magnetic permeability of the vacuum, and W is the average dissipated power. Also, as stated, the series resistance can be calculated at various frequencies (ω) for a given solenoid parameters (n , g , and a) as a function of resistivity (ρ). Figure 5 is a graph of series resistance due to inductive loss as a function of sample fluid conductivity for an experimental solenoid. The series resistance increases as the square of the frequency and correspondingly Q of the antenna will decrease at higher frequency in the presence of a conductive environment.

[0061] In addition to the above mentioned sample losses, there can also be dielectric losses. This loss mechanism arises from the distributed capacitance of the coil. The electric field associated with the distributed capacitance of the coil passes through the sample, which dissipate power. This loss can be reduced or eliminated if a Faraday shield is inserted between the coil and the sample (see "Radiofrequency Losses in NMR Experiments on Electrically Conducting Samples," DG Gadian, FNH Robinson, JMR, 34(2) 449–455, (1979)). In an embodiment of the invention, as

illustrated in Figure 16, a Faraday shield 195 is disposed between the coil 190 and the flow line 110.

[0062] The dielectric loss is calculated as follows: As treated above, this loss mechanism comes about from the distributed capacitance of the turns in the inductor coil (see "The Sensitivity of the Zeugmatographic Experiment Involving Human Samples," DI Hoult, PC Lauterbur, JMR, 34, 425-433, (1979)). The equivalent circuit is shown in Figure 4, where L_0 and C_0 are the inductor and capacitor of the tuned circuit, C_1 is the (lossless) capacitance from coil to sample, C_2 and R_d represent the lossy sample.

[0063] The complex admittance of the circuit containing C_1 , C_2 and R_d is given by

[0064] $Y = Y_{\text{real}} + iY_{\text{imag}}.$ (10)

[0065] $Y_{\text{real}} = (\omega^2 R_d C_1^2) / (1 + \omega^2 R_d^2 (C_1 + C_2)^2)$ (11)

[0066] $Y_{\text{imag}} = (\omega C_1 - \omega^3 R_d^2 C_1 C_2 (C_1 + C_2)) / (1 + \omega^2 R_d^2 (C_1 + C_2)^2)$ (12)

[0067] The Y_{real} is zero, when $R_d = 0$ and also when $R_d = \infty$ and in between Y_{real} goes through a maximum at

[0068] $R_d = 1/(\omega (C_1 + C_2)).$ (13)

[0069] It also means that the parallel impedance across L and C goes through a minimum and the quality factor (Q) due to

dielectric loss also goes through a minimum at that point. The parallel impedance is inversely related to the series impedance.

[0070] The time constant ($R_d * C_2$) of the dielectric relaxation time is determined from the dielectric relaxation theory (see "Radiofrequency Losses in NMR Experiments on Electrically Conducting Samples," DG Gadian, FNH Robinson, JMR, 34(2) 449–455, (1979)); and it is found to be

[0071] $R_d C_2 = \kappa \epsilon_0 / \sigma, (14)$

[0072] where σ is the conductivity of the sample, κ is the relative dielectric constant of the sample and ϵ_0 is the permittivity of free space ($= 8.85 \times 10^{-12}$ F/m).

[0073] The series resistance is given by

[0074] $R_D = (\omega^4 L^2 R_d C_1^2) / (1 + \omega^2 R_d^2 (C_1 + C_2)^2) (15)$

[0075] The dielectric loss (R_D) can be calculated as a function of the conductivity of the sample (σ) using equations (14) and (15). The capacitor values of C_1 and C_2 were found to be 0.8 pF and 2 pF respectively for a coil used in an experiment.

[0076] The series resistance due to dielectric loss is calculated at different frequencies and it is plotted in Figure 6. The conductivity at which the resistance goes thru a maximum

is shifted towards lower and lower conductivity as the frequency is decreased. The tuning frequency will shift to lower frequencies because of the imaginary term in Equation (12).

[0077] The series resistance of the tuned antenna for a conductive sample is determined by all three loss mechanisms treated above. The quality factor of the tuned antenna is given as

[0078] $Q = \omega L / (R_{int} + R_L + R_D)$ (16) where ω is the frequency, L is the inductor, R_{int} is the series resistance due to internal losses, R_L is the series resistance due to inductive losses, and R_D is the series resistance due to dielectric losses.

[0079] The dielectric loss at lower conductivities is more than the inductive loss (see Figures 5 and 6), whereas at higher conductivities the inductive losses dominate the dielectric loss. The dielectric and inductive loss are both less at lower frequencies than at higher frequencies.

[0080] Referring to Figure 17, there is shown a flow diagram of a routine for controlling a processor or processors, uphole and/or downhole, in accordance with an embodiment of the invention. If desired, some of the steps may even be performed remote from the wellsite.

[0081] The block 1710 represents determining and/or measuring

of n , L , l_a , r_a , and r_o for the antenna coil 190 in the flow-line. The Q of the antenna is measured (block 1720) without a sample in the flowline. (Alternatively, the reference Q of the antenna coil could be measured with a reference material in the flow line). The routine of Figures 19–20, to be described, can be utilized. The determinations and/or measurements represented by the blocks 1710 and 1720 can be performed, a priori, uphole. The block 1730 represents positioning the formation testing device 100 at a depth level of interest in the borehole, and the block 1740 represents setting of the device and drawing formation fluid into the flow line. As is known in the art, a pretest can be implemented before the fluid to be tested is drawn. The block 1750 represents measuring of the Q of the coil 190 with formation fluid in the flow line. Again, the routine of Figures 19, 20 can be utilized. Then, as represented by the blocks 1760 and 1770, Q_L is determined from a difference in reciprocals, and R_L is determined using relationship (1). Then, the fluid conductivity, σ , can be determined using equation (9).

[0082] The quality factor, Q , of the coil can be determined in any suitable manner, one embodiment being illustrated in conjunction with Figures 18 and 19. Figure 18 shows the

flow line 110 and coil 190, which, as noted above, can, if desired, serve dual purpose as an NMR flow line antenna. In the Figure 18 embodiment, excitation is provided by constant current source 1810 and an antenna shown as calibration loop 1820. A frequency generator 1830, under control of the processor, provides input to the constant current source 1810. In operation, the loop 1820 is fired at a preselected for a predetermined time, for example a few milliseconds. The detector 1850 is used to measure the voltage sensed by the coil. The procedure is then repeated for the next pre-selected frequency. A flow diagram of the process is shown in Figure 19. The block 1905 represents initialization to a first frequency, and the blocks 1910 and 1920 respectively represent firing of the loop 1820, and measurement and storage of the voltage sensed by the coil 190. The measurement data is processed in accordance with the routine of Figure 20, to be treated momentarily. Determination is then made (decision block 1930) as to whether the last preselected frequency has been employed. If not, the frequency generator is set to the next preselected frequency (block 1935), and the loop 1925 continues until all of the preselected frequencies have been used. Inquiry is then made

(decision block 1960) as to whether another cycle of data collection is to be performed and, if so, block 1905 is re-entered, and the loop 1965 continues as further measurements are made and data collected.

[0083] In the graph of Figure 21, the voltage induced in the antenna coil 190 is shown plotted as a function of frequency. The voltage maximum, V_{\max} , is at a frequency F_o . The frequencies at which the detected voltages are

$$V_{\max}/\sqrt{2}$$

are designated F_1 and F_2 . The quality factor, Q , is the ratio of F_o to the bandwidth, $(F_2 - F_1)$; that is, $Q = F_o / (F_2 - F_1)$. In the flow diagram of Figure 20, The block 2010 represents determination of the frequency (F_o) at which the detected voltage is a maximum. Then, as represented by the block 2020, the frequencies at which detected voltages are

$$V_{\max}/\sqrt{2}$$

are determined, these being designated F_1 and F_2 . Then, the quality factor, Q can be computed from $Q = F_o / (F_2 - F_1)$ as set forth in block 2030. A loop 2035 continues as further measurements are made and data collected.

[0084] As seen from step 1760 of the flow diagram of Figure 17, the component Q_D is not considered in this embodiment. The use of a Faraday shield, as in Figure 16, will reduce or

eliminate the R_D component, strengthening the validity of this approximation. In a further embodiment hereof, in the absence of a Faraday shield, the dielectric constant of the formation fluid in the flow line is determined, as well as the conductivity of the fluid. By using a plurality of frequencies, thereby tuning the antenna at different frequencies by changing the effect of the capacitance in parallel with the inductor in the circuit model, both dielectric constant and conductivity can be determined. In an example of this embodiment, Q is measured at two frequencies. Then, the two unknowns of equations (9) and (15), namely conductivity, σ , and dielectric constant, K , are determined, such as by simultaneous solution of these equations.

[0085] In a further embodiment hereof, the pickup voltage sensed at the coil 190 upon excitation with the calibration loop can be utilized to obtain the formation fluid resistivity, since the pickup voltage is proportional to Q .

[0086] Experimental results will next be described. A solenoid coil was wrapped around a test tube with an id of 0.197" and the coil has 8 turns, the diameter of the coil was 0.2", and the length of the coil was 0.5". HP Impedance/Gain-Phase Analyzer was used to measure the quality factor of the antenna and the series resistance was

determined from the equivalent circuit of the data. The conductivity was measured using a conductivity meter, WTW, model # LF 330.

[0087] The coil was tuned to a particular frequency using a capacitor in parallel with the coil. The conductivity of the water sample was varied with varying sodium chloride concentration. The Q of the tuned circuit was measured as a function of the conductivity of the water sample. The Q measurement was repeated at various frequencies as a function of salt concentration in water.

[0088] The theoretical series resistance calculated using equations (9) and (15) was compared with the experimental data, and substantial agreement between the theory and the experimental data was observed.

[0089] Figure 7 shows experimental data of series resistance as a function of conductivity at various frequencies. Figure 8 is a graph showing calculated and experimental series resistance as a function of sample conductivity at 2.37 MHz. At this operating frequency, dielectric loss is negligible, even without a Faraday shield. Figures 9 and 10 are graphs showing calculated and experimental series resistance as a function of sample conductivity at 9.88 MHz. In Figure 10, lower conductivities are shown in further detail. Fig-

ures 11 and 12 are graphs showing calculated and experimental series resistance as a function of sample conductivity at 19.655 MHz. Figure 12 shows lower conductivities in further detail. Figure 13 is a graph showing theoretical and experimental data of quality factor, Q , at 2.37 MHz. Figure 14 is a graph showing theoretical and experimental data of quality factor, Q , at 9.8 MHz. Figure 15 is a graph showing theoretical and experimental data of quality factor, Q , at 19.655 MHz. Figure 22 is a graph showing theoretical and experimental data of series resistance as a function of sample conductivity at 18.225 MHz, with use of a Faraday shield.

[0090] While the invention has been described using a limited number of embodiments, those skilled in the art, having the benefit of this disclosure, will appreciate that other variations are possible without departing from the scope of the invention as disclosed herein. Accordingly, the scope of the invention should be limited only by the attached claims.